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The Evolution of Space and Time

The attention of the physicists was recently led towards the fundamental notions of space and time, as new experimental facts obliged us to alter them; nothing can better demonstrate the empirical origin of these notions than their progressive adaptation, still not finished, with the increasing subtlety of human experiments.

I would like to show that the form, usually insufficiently analyzed, in which these notions arose up to the present, was determined and conditioned by a particular and provisional synthesis of the world by the mechanistic theory. Our space and time were given as required by rational mechanics.

The new synthesis that is increasingly powerful, and which is represented by the electromagnetic theory of physical phenomena, corresponds to space and time (especially time) which are different from those of mechanics, and which are favored by our current means of experimental investigation. It is particularly remarkable that the increasing perfection of our measurement methods, which accuracy has been pushed beyond a billionth, obliges us to continue the adaptation to the facts of the most fundamental categories of our thought. For the philosopher, there is an excellent opportunity to penetrate the intimate nature of these categories, when they are still in the process of evolution, to see them living and transforming before his eyes.

[32] There is neither space nor time *à priori*: to every moment, every level of perfection of our theories of the physical universe corresponds a conception of space and time. Mechanics implied the old conception, electromagnetism requires a new one, and nothing permits us to say that this is the definite one.

It is also difficult for our brain to get used to these new forms of thought: reflection is particularly delicate and can only be aided by the formation of an adequate language.

This is the task, for facilitating the evolution of mankind, for which today philosophers and physicists have to work together.

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All living beings have the capability of internal and spontaneous expansion, that is even greater when they are better adapted to the milieu in which they arose. When, as a result of this expansion, an encounter takes place between individuals or species, there may be mutual adaptation, or, if accordance is impossible, a conflict resulting in the survival of the fittest, which generally assimilates the substance of the other and imposes it a new form that life seems to have judged better.

It is the same for our physical theories: some are particularly well established, have succeeded brilliantly in the interpretation and the grouping of a category of experimental facts, to which they impose a form; and then they develop (spontaneously and in agreement with this form) this rhythm of their own, by taking the already known but scattered facts as substance of the building which they construct, and those facts to which they are directed to learn, and finally those facts already established as synthesis in the form of various theories that will be absorbed by the new one after coming in conflict with them.

Just as the growth effort of living beings is facilitated by organic syntheses already realized in other beings that were absorbed, the new theory conserves and uses more or less completely the body of facts already established by the theories over which it triumphed.

We are now witnessing a conflict of this kind between two conceptions of the universe that are of particular importance [33] and beauty: the rational mechanics of GALILEO and NEWTON on the one hand, and on the other hand the electromagnetic theory in the advanced form as it was given by MAXWELL, HERTZ, and LORENTZ.

Rational mechanics was created for the interpretation of the phenomena of visible motion and it succeeded admirably. All the scientific effort of the eighteenth century and much of the nineteenth was devoted to extend this capability to explain all physical phenomena by applying these laws to the motions of various invisible material particles or fluids.

Thus developed the doctrine known as mechanics, by the fusion of rational mechanics and of the atomistic hypotheses. The success was great in certain domains, such as the kinetic theory of fluids for example, less in others such as elasticity and optics.

We shall not forget, that it was only the atomistic conception that was often made responsible for the failure of mechanics, today however it is definitively established by indisputable experimental facts, and its association with the electromagnetic theory proved its remarkable fertility in the last fifteen years. What really seems to be questionable, is the application of mechanical laws to the invisible motions, which were at first established for visible motions, and even for them it represents only a first approximation, albeit it is excellent.

The theory of electromagnetic phenomena such as we have it today, is certainly independent of the laws prescribed in the motion of matter by rational mechanics, although it appears to be involved in certain fundamental definitions: the best evidence of this independence is provided by the contradictions that currently exist between the two syntheses.

Electromagnetism is just as remarkably adapted to its original domain, as rational mechanics was adapted to its domain; with its notions of a very special medium that transmits the actions step by step, the electric and magnetic fields characterizing the state of this medium, with very particular forms of relations between the simultaneous variation of these fields in space and time; electromagnetism constitutes a discipline, [34] a way of thinking that is quite different, quite separated from mechanics, and endowed with an immense force of expansion that has assimilated the immense domains of optics and radiant heat to which mechanics remained incapable, and every day it provokes new discoveries in this field. Electromagnetism has conquered much of physics, invaded chemistry, and grouped an immense number of facts that were hitherto formless and disconnected.

Of our two opposing theories, the first possesses the titles of nobility of a longstanding history, and the authority of having seen the verification of its laws by the most distant stars and the molecules of the most tenuous gas; the second which is younger and more alive, is much better adapted to the entirety of physics and possesses an inner force of growth that the other seems to have lost.

MAXWELL had thought, that it's possible to reconcile the two theories and to show that electromagnetic phenomena are susceptible of mechanistic interpretations; but his demonstration, made elsewhere on the particular case of phenomena presented by closed currents, proves only that the two syntheses share common characteristics, such as the common property of leaving certain integrals stationary, but they may remain irreconcilable with other characteristics.

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These differing characteristics have been recently demonstrated by new experimental facts, by the negative result of all experiments, some of extraordinary delicacy, which were attempted to try to demonstrate the total uniform translational motion of a material system by experiences within this system, to show the absolute translational motion.

We knew already, and rational mechanics is perfectly consistent with this fact, that mechanical experiments on visible motions, performed within a material system, do not permit to demonstrate a uniform translational motion of the entire system, but on the contrary for rotational motion [35] it can be achieved by the FOUCAULT pendulum or the gyroscope. In other words, according to the mechanical point of view, the collective uniform translation has no absolute sense, rotation on the contrary has one.

But within a material system, other experiments can be tried which involve electromagnetic or optical phenomena. Electromagnetic theory involves a medium for its explanation, the aether, which transmits the electrical and magnetic actions and in which electromagnetic disturbances (light in particular) propagate with a determined velocity.

It was hoped that if a material system moves with a uniform translation in respect to this medium, electromagnetic or optical experiments inside the system permit the demonstration of this translation.

As the Earth, in its annual motion, possesses a translation velocity which is constantly varying by amounts of up to sixty kilometers per second for the relative velocity corresponding to two diametrically opposed positions of the globe in the orbit, it was hoped that at least at certain times of the year, observers on Earth and their equipment will move in relation to the ether with a velocity of this order and might be able to demonstrate their motion.

This could be expected, because by combining the fundamental equations of electromagnetism, which were believed to be accurate for stationary observers in the aether, with the ordinary notions of space and time as required by rational mechanics, that these equations would change their form to observers moving in the ether, and the differences for velocities like that of Earth in its orbit should be visible in certain experiments of extraordinary delicacy.

But the result was found consistently negative, and independent of any interpretation, we can state as an experimental fact the contents of the following principle, namely that of relativity:

If different groups of observers are in uniform translation against each other (such as observers attached to Earth for different positions of the latter in its [36] orbit) all mechanical and physical phenomena follow the same laws for all these groups of observers. None of them, by experiments inside of the material system to which they are attached, can demonstrate the uniform translation of the whole system.

From the electromagnetic point of view we can still say that the fundamental equations, in their usual form, are valid for all these groups of observers at the same time, that everything happens for each one as if it were stationary relative to the aether.

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So it's an experimental fact that the equations between physical quantities by which we translate the laws of the outside world, must have exactly the same form for different groups of observers, for various systems of reference in uniform translation relative to each other.

This requires, in the language of mathematics, that these equations admit of a group of transformations corresponding to a change of reference system to another moving relative to it. The equations of physics must be preserved for all transformations of this group. In such a transformation, when one moves from one reference system to another, measures of various magnitudes, especially those that are related to space and time, are changed in a manner that corresponds to the structure of these notions.

Now the equations of rational mechanics actually admit of a group of transformations corresponding to the change of reference system, and the part of that group that is related to measurements of space and time is in accordance with the usual form of these notions.

It is the great merit of H. A. LORENTZ to have shown that the fundamental equations of electromagnetism also admit of a group of transformations that allow them to take the same form when we pass from a reference system to another; *this group deeply differs from the preceding concerning the transformations of space and time.*

[37] We must choose: if we want to maintain an absolute value of the equations of rational mechanics and of space and time corresponding to them, we must consider as false those of electromagnetism, and reject the admirable synthesis that I mentioned above, and introduce for example an optical emission theory with all the difficulties it entails and which were dismissed over fifty years ago. However, if we want to keep electromagnetism, we must adapt our minds to new concepts that are required for space and time and consider rational mechanics as having no more than the value of a first approximation, but it is largely sufficient when it comes to motions which velocity does not exceed a few thousand kilometers per second. Electromagnetism, or the laws of mechanics admitting the same transformation group as it, alone permits to go further and take the important place of rational mechanics.

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To better highlight the contrast between the two syntheses, it is easier to merge, as proposed by MINKOWSKI, the two notions of space and time in the more general notion of world.

The world is the ensemble of all events: an event consists in the fact that it happens, or there is something in a certain place at a certain moment. If a reference system is given, that is to say a system of axes connected with a certain group of observers, any event is determined in terms of its position in space and time by four coordinates measured in this reference system, three for space and one for time.

If two events measured in a certain reference system are given, they generally differ in both space and time, and occur in different places at different times. To a couple of events their corresponds a spatial distance (the points [38] where the two events are happening) and a temporal interval.

We can define time by all the events that follow one another at one point, for example in the same portion of matter in relation to a reference system, and define space by all the simultaneous events. This definition of space corresponds in effect to that the shape of a moving body is defined by the set of simultaneous positions of the various portions of matter it contains, its various material points, or by all events posed by the simultaneous presence of these different material points. If we agree to call with MINKOWSKI the *world line* of a portion of matter that may be in motion relative to the reference system, all events that occur in that portion of matter, then the shape of a body at a given moment is determined by the set of simultaneous positions on the world lines of various material points which constitute this body.

The notion of simultaneity of events happening at different places is fundamental for the very definition of space when a body in motion is concerned, and this is generally the case.

In the ordinary conception of time one attributes to simultaneity an absolute sense, supposedly independent of the reference system; it is necessary that we analyze more closely the content of this generally tacit hypothesis.

Why do we usually not admit that two events that are simultaneous for a certain group of observers, may not be simultaneous for another group moving relative to the first, or, equivalently, why don't we admit that a change of reference system permits to reverse the order of temporal succession of two events?

This is obviously a consequence of our implicit admission, that if two successive events occur in a certain order for a given reference system, the one that occurred first would be able to intervene as a cause and change the conditions under which the second occurs, regardless of their spatial separation.

In these circumstances it is absurd to suppose that for [39] other observers, for another reference system, the second event, the effect, may occur before its cause.

The absolute nature usually admitted to the notion of simultaneity is a consequence of the implicit hypothesis that causality can propagate with infinite velocity, the hypothesis that an event can occur simultaneously as cause at any distance.

This hypothesis is consistent with the mechanistic conception and since it is required by the concept of the perfect rigid body of rational mechanics, for example an inextensible bell cord that is interposed between the two points where the events occur, would instantly signal the occurrence of the first event to the point where the latter will occur, and would consequently allow to take the first in account, to utilize it as cause under the conditions which determine the second. So there is mutual adaptation of rational mechanics and ordinary conceptions of space and time in which the simultaneity of two distant events in space has an absolute sense.

We are therefore not surprised to find that in the transformation group which preserves the equations of mechanics, *the time interval of two events is conserved, and it is measured in the same way by all groups of observers regardless of their relative motions.*

It is different for the spatial distance: it's a simple fact and contained in the usual notions that the spatial distance of two events generally has no absolute sense and depends on the reference system that is used.

A concrete example will show how the spatial distance of the same two events may be different for different groups of observers in relative motion to each other. Imagine a hole in the floor of a car in motion relative to the ground, and then one drops two objects in succession: the two events that constitute the exits of the two objects through the hole, occur at the same point for observers related to the car, but at different points for observers related to the ground. The spatial distance of these two events is zero for the first observers, but for the other it is equal to the product [40] of the velocity of the car with the time interval between the fall of the two objects.

Only if the two events are simultaneous their distance in space has an absolute sense so that they don't vary with the reference system. It follows immediately that the dimensions of an object, the length of a ruler for example, has also an absolute sense, and are the same for observers at rest or in motion relative to this object: we have noticed that for any observation, the length of a ruler is the distance between two simultaneous positions of the ends of the ruler, that is to say the spatial distance of two simultaneous events, two simultaneous occurrences of both ends of the ruler. We have seen that simultaneity, as well as the spatial distance of two simultaneous events, have an absolute sense in the usual conceptions of time and space.

Given any two successive events, *i.e.* two events separated in time, we can always find a reference system in which these two events coincide in space, with observers to whom these two events happen at one point. It will indeed be sufficient to give these observers, compared to the original reference system, a motion so that they attend the first event and next they attend the second event, so that for them the two events occur at the same point close to them; it suffices to give the observers a velocity equal to the ratio of the spatial distance to the time interval between both events in the original reference system, and this is always possible if the time interval is not zero, *i.e.* if the two events are not simultaneous.

What can be achieved for space, namely the coincidence of two events in space by a suitable choice of reference system, cannot be achieved for time since the time interval of two events has an absolute sense, it is measured in the same way in all reference systems.

There is an asymmetry between space and time as they are habitually given, that disappears in the new concepts: the interval in time, as well as the distance in [41] space will become variable with the reference system, that is, with motion of the observers.

In the new concepts, only one case remains and must remain where the change of reference system is ineffective: it is where the two events coincide in both space and time: this double coincidence must indeed have an absolute sense since it is the encounter of the two events, and this encounter may produce a phenomenon, a new event, which necessarily has an absolute sense. Remember the previous example, if the two objects coming out of the car by the same hole, leave simultaneously *i.e.* if their endpoints coincide in both space and time, it may result in a shock and the breaking of the objects, and this shock phenomenon has an absolute sense, so that in any conception of the universe, electromagnetic or mechanical, the coincidence in both space and time if it exists for a group of observers, cannot be denied by another group regardless of their motion relative to the first. For those who see the car passing by, as for those who are there, the two objects will break each other because they come together at the same point.

Except for this very special case, it is easy to see that the electromagnetic conception requires a major overhaul of the notion of world. The equations of electromagnetism imply, in their usual form, that an electromagnetic disturbance, *e.g.* a light wave, propagates in vacuum with the same velocity in all directions, equal to three hundred thousand kilometers per second.

The newly established experimental facts have shown that if these equations are exact for a group of observers, they should also be exact for all others regardless of their motion relative to the first, resulting in the paradoxical fact that a light disturbance must be spread with the same velocity for different groups of observers in motion relative to each other. A first group of observers sees a light wave propagate in a certain direction with a velocity of three hundred thousand kilometers per second and sees another group of observers following this wave with an [42] arbitrary velocity; however, for this second group, the light wave will move relative to them with the same velocity of three hundred thousand kilometers per second.

EINSTEIN first showed how this necessary consequence of the electromagnetic theory is sufficient to determine the characteristics of space and time required by the new conception of the world. It is conceivable, according to the above, that the velocity of light must play an essential role in the new formulations: it is the only velocity that is preserved when passing from one reference system to another and plays in the electromagnetic world the role which is played by the infinite velocity in the mechanical world. This will be clear from the results that follow.

For any pair of events, changing the reference system changes both the distance in space and time interval, but in view of the importance of these changes, we are led to classify couples of events into two major categories for which time and space play symmetric roles.

The first category consists of pairs of events for which their spatial distance is greater than the path traveled by light during the time interval, that is to say, when the emission of light signals accompanies the production of two events, each will take place *before* the passage of the signal from the other. Such a relationship has an absolute sense, that is to say, it is valid for all reference systems, when it is valid for one of them.

The transformation equations required by the electromagnetic theory show, that in this case the order of succession of two events in time has no absolute sense. If, for a first reference system, the two events follow each other in a certain order, this order will be reversed for observers moving in respect to the first with a velocity less than that of light, that is to say at a physically attainable velocity.

It is evidently impossible for two events whose order of succession may be reversed, are united by a relation of cause and effect, because if such a relationship would exist between our two events, some observers would see the cause after the effect, which is absurd.

[43] However, since the spatial distance of our two events is greater than the path traveled by light during their time interval, the first cannot be involved in the occurrence of the other and the second cannot be informed of the first, except if the causal connection could propagate with a velocity exceeding that of light. We must therefore, according to the above, eliminate this possibility: Causality, whatever its nature, must not propagate with a velocity exceeding that of light, there should be no messenger or signal which can travel at more than three hundred thousand kilometers per second.

We must therefore admit that an event cannot act instantly as a remote cause, that its impact can only be felt immediately on the position or the point where it took place, and subsequently at increasing distances, and increasing with at most the velocity of light. In this view, the new concept plays the same role that was played in the old concept by the infinite velocity, and represents the velocity limit at which causality can propagate.

Hence we see that the current antagonism between mechanics and electromagnetism only manifests in a new form the opposition between two conceptions which followed one another in the development of electrical theories: that of instantaneous action at a distance consistent with mechanics, and transmission through a medium, by direct action as introduced by FARADAY. This old opposition occurs nowadays even for the most fundamental concepts.

From the foregoing various consequences follow: firstly it is impossible for a portion of matter to move in relation to another with a velocity exceeding that of light. This paradoxical result is contained in the formulas that led to the new kinematics of velocities: the composition of any number of velocities below the velocity of light always gives a lower velocity than that of light. Similarly as in the ordinary conception, the composition of any number of finite velocities still gives a finite velocity.

[44] We can say then that no action at a distance, as gravitation for example, can propagate faster than light and we know that this condition is not refuted by the astronomical results currently established.

Finally it is necessary to abandon the perfectly rigid body of mechanics in which we could find a way to signal immediately at a distance and to establish a causal connection propagating faster than light. Nothing of what we know about real rigid bodies is opposed to this, that any action or any wave must be propagated less fast than light; elastic waves in the most rigid solids, in fact propagate with a much lower velocity. The important thing is that we must reject the conception of a perfect rigid body, of a body that could be put in motion simultaneously at all its points.

We can summarize the above reasoning as follows: if there were a signal that could propagate with a velocity exceeding that of light, observers could be found for whom this signal would have arrived before it departed, and for whom the causal connection allowed by the signal would be reversed: we could telegraph in the past, as it was said by EINSTEIN, and we consider that this would be absurd.

The two events of the pair in question, with no definite order of succession in time, are thus necessarily without possible mutual influence, so they are truly independent events. Evidently, having no causal connection between them, they can not follow upon each other in the same portion of matter, and can not belong to the same world line in the life of a single being. This impossibility is in accordance with the fact that, to be successively the seat of these two events, this portion of matter should move with a velocity exceeding that of light.

Both events cannot be brought to coincide in space for any choice of reference system, but they can be brought to coincide in time: since their sequence can be reversed, there are reference systems for which the two events are simultaneous.

We can call *pairs in space* those pairs of events [45] that have just been considered and to which the order of succession in time has no absolute sense, but are spatially distant in an absolute way.

It is noteworthy that, while the spatial distance of two events can not be canceled, it reaches a minimum precisely for reference systems in which the two events are simultaneous.

Hence the following statement:

The spatial distance of two events that are simultaneous for a certain group of observers, is shorter for them than for all other observers in arbitrary motion relative to them.

This statement contains, as a particular case, what is called the LORENTZ contraction, that is to say, the fact that the same ruler considered by different groups of observers, some resting, others in motion relative to it, is shorter for those who see it passing by as for those who are attached to it. We have already seen that the length of a ruler for observers who see it passing by, is defined by the distance in space of two simultaneous positions (for those observers) on both ends of the ruler. According to the preceding this distance will be shorter for those observers than for all others, especially those attached to the ruler.

We also easily understand how the LORENTZ contraction can be reciprocal, that is to say how two rulers that are equal when at rest, appear mutually shortened when they slide against one another, and observers attached to one of the rulers will see the other one shorter than its own. This reciprocity holds, because observers associated with the two rulers in motion relative to each other don't define simultaneity the same way.

We will find for the pairs of events of the second category, properties exactly correlative to the preceding one by permutation of space and time. These pairs, which I will call *pairs in time*, are defined by the following condition, which has an absolute sense: the spatial distance of two events is less than the path traveled by light during their time interval; otherwise said, the second event occurs *after* the passage of the light signal whose emission coincides in [46] space and time with the first. This introduces, from the point of view of time, an asymmetry between the two events, as the first occurs before the passage of the light signal whose emission coincides in space and time with the second event, while the second occurs after the passage of the light signal which accompanies the first one. A causal connection may exist at least by light between the two events, so the second has been informed of the first, and this requires that the order of succession has an absolute sense, and cannot be reversed by any change of reference system. We immediately see that such a reversal would require a velocity exceeding that of light for the second reference system in respect to the first.

Two events between which thus exists a real possibility of influence, when they cannot be brought to coincide in time, can always be brought to coincide in space by a suitable choice of reference system. Especially if the two events belong to the same world line, following each other in an absolute order in the life of a portion of matter, they will coincide in space for observers attached to that portion of matter.

In correlation to what was happening earlier, if the time interval of two events cannot be canceled, it passes by a minimum precisely for the reference system in which the two events coincide in space.

Hence the statement:

The time interval between two events that coincide in space, which follow each other at the same point for a certain reference system, is less for it than for any other system in arbitrary uniform translation relative to the first.

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In all the above, the employed reference systems are supposed to possess uniform translational motion: for only such systems, observers associated with them cannot experimentally detect their collective motion, only for such systems the equations [47] of physics must hold their shape when switching from one to another. For such systems it is thus, as if they were stationary relative to the aether: a uniform translation in the aether has no experimental sense.

But because of this it should not be concluded, as has sometimes happened prematurely, that the concept of aether must be abandoned, that the aether is non-existent and inaccessible to experiment. Only a uniform velocity relative to it cannot be detected, but any change of velocity, or any acceleration has an absolute sense. In particular it is a fundamental point in the electromagnetic theory that any change of velocity or any acceleration of an electrified center is accompanied by the emission of a wave that propagates in the medium with the velocity of light, and the existence of this wave has an absolute sense; and conversely any electromagnetic wave, light for example, has its origins in the change of velocity of the electrified center.

We therefore have hold on the ether through accelerations, and acceleration has an absolute sense as determining the production of waves from matter that has undergone a change in velocity, and the aether manifests its reality as the vehicle, as the carrier of energy transported by these waves.

The theory provides the opportunity to demonstrate, by electromagnetic or optical experiments, any acceleration of the collective motion of a material system by means of experiments inside this system, if only in finding the wave emission by electrified bodies related to the system, which are immobile relative to it. We also know that if the acceleration of the collective motion is communicated to the system by external actions that are exerted, contrary to what happens with gravity, only on parts of the system, we have many other means to demonstrate it, for example, strains within the system through which the acceleration is transmitted from portions of the system, that suffer external actions, to other portions that do not undergo them.

In a uniform gravitational field, where each portion of the system would suffer direct external action which would communicate the overall acceleration, as in the projectile of JULES VERNE, similar reactions do not occur [48], but, as I said above, the possibility of electromagnetic or optical experiments to detect the change of velocity of the collective motion would remain: the laws of electromagnetism are not the same in respect to axes attached to this material system as in respect to axes in collective uniform motion of translation.

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We will see the appearance of this absolute character of acceleration in another form.

Consider a portion of matter in arbitrary motion and the sequence of events that constitute the life of this portion of matter, its world line.

For two of these events that are sufficiently close, observers in uniform motion who attend these two events successively can be regarded as related to this portion of matter, the velocity change of the latter being imperceptible in the interval between the two events. For these observers, the time interval between the two events constitute an element which we call the *proper time* of the portion of matter, will be shorter than for any other group of observers associated with a reference system in arbitrary uniform motion.

If we now take any two events in the life of our portion of matter, then their time interval measured by observers in non-uniform motion who will constantly monitor the portion of matter, will be, by integrating the previous result, shorter than for the reference system in uniform motion.

In particular, in this reference system the two events considered may be taking place at the same point, in relation to which a portion of matter has traveled a closed cycle and has come back to its starting point thanks to its non-uniform motion. *And we can say that for observers related to that portion of matter, the time period elapsed between the departure and return, i.e. the proper time of the portion of matter will be shorter than for observers who would have stayed connected to the reference system in uniform motion.* That portion of matter [49] will have aged less between its departure and its return than if it had not been accelerating, *i.e.* as if it had remained stationary relative to a reference system in uniform translation.

We can still say that it is sufficient to be agitated or to undergo accelerations, to age more slowly, and we'll see in a moment how much you can expect to get in this way.

Giving concrete examples: Imagine a laboratory attached to the Earth, which motion can be considered as uniform translation, and in this laboratory there are two perfectly identical samples of radium. What we know about the spontaneous evolution of radioactive materials allows us to say that if these samples are kept in the laboratory, they will lose both their activity the same way over time and their activities remain continuously equal. But then send one of these samples with a sufficiently high velocity and then bring it back to the laboratory; this requires that at least at certain times this sample has undergone accelerations. We can say that on return, its proper time between departure and return is less than the measured time interval between these events by observers attached to the laboratory, so that it has less evolved than the other sample and therefore it will be more active than the latter; it will have aged less, having been more agitated. The calculation shows that for a difference of one ten-thousandth between changes of activity of two samples, it will be necessary to maintain (during separation) the velocity of the traveling sample at approximately four thousand kilometers a second.

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Before we give another example, yet let us represent our result in a different light. Suppose that two pieces of matter meet for the first time, separate and meet again. We can say that observers attached to the portions during the separation, will not evaluate that duration in the same way, as some have not aged as much as the others. It follows from the foregoing that those have aged the least, for whom the [50] motion during separation was most distant from uniform, and who have suffered the greatest accelerations.

This remark provides the means for any among us who wants to devote two years of his life, to find out what the Earth will be in two hundred years, and to explore the future of the Earth, by making in his life a jump ahead that will last two centuries for Earth and for him it will last two years, but without hope of return, without possibility of coming to inform us of the result of his voyage, since any attempt of the same kind could only transport him increasingly further.

For this it is sufficient that our traveler consents to be locked in a projectile that would be launched from Earth with a velocity sufficiently close to that of light but lower, which is physically possible, while arranging an encounter with, for example, a star that happens after one year of the traveler's life, and which sends him back to Earth with the same velocity. Returned to Earth he has aged two years, then he leaves his ark and finds our world two hundred years older, if his velocity remained in the range of only one twenty-thousandth less than the velocity of light. The most established experimental facts of physics allow us to assert that this would actually be so.

It is amusing to realize how our explorer and the Earth would see if they could, by light signals or by wireless telegraphy, mutually stay in constant communication during their separation, and thus understand how the asymmetry between two measures of the duration of separation is possible.

As they move away from each other with a velocity close to that of light, each seems to flee before the electromagnetic or optical signals that were sent to the other, so that there will be a very long time to receive signals that were emitted during a given time. The calculation shows that each of them will see the other live two hundred times slower than usual. During the year of this distant motion, the explorer will receive the news from Earth of the first two days after his departure, and during this year he will see the Earth make the motions of two days. Moreover, [51] for the same reason, the radiation he receives from the Earth during this time has wavelengths that are two hundred times greater due to the DOPPLER principle. What seems to him as light radiation by which he can see the Earth, has been emitted as extreme ultraviolet radiation, maybe close to ROENTGEN rays. And if one wants to maintain communication between them by HERTZian signals or by wireless telegraphy, the explorer who brought with him a receiving apparatus with a certain antenna length, the transmission devices used by the Earth during these two days of departure must have a antenna length two hundred times shorter than his.

During the return, conditions are reversed: for each of them see the life of the other as remarkably fast, two hundred times faster than usual, and during the year for him to return the Explorer sees the Earth perform the actions of two centuries: so it is understood how he can find the Earth aged by two hundred years. During this period he will also see waves that are bright for him, but they will be emitted as far infrared rays of around one hundred microns in wavelength as RUBENS and WOOD have recently discovered in the emission spectrum of a WELSBACH mantle. For him to continue to receive radio signals of Earth, it shall, after the first two days and for two centuries thereafter, use a transmitting antenna two hundred times longer than that of the traveler, forty thousand times longer than that used during the first two days.

To understand the asymmetry, it is noteworthy that the Earth will spend two centuries to receive the signals sent by the explorer during his motion away from it which lasted a year: he will live during this time in his ark a life two hundred times slower, while he will make the gestures of a year. In the two centuries during which the Earth sees the observer moving away, it must, to receive the HERTZian signals emitted by him, use an antenna two hundred times longer than that of the observer. At the end of two centuries the news of the encounter of the projectile with the star will come to Earth, that marks the beginning [52] of the return voyage. The arrival of the traveler will occur two days afterwards during which the Earth will see him living two hundred times more quickly than usually, and it will see him achieving the gestures of another year to find him only two years aged at the return. During these two last days, to receive news of him, the Earth will have to use a reception antenna two hundred times shorter than the antenna of the traveler.

Thus the asymmetry - which occurred because only the traveler, in the middle of his journey, has undergone an acceleration that changes the direction of his velocity, and which brings him back to the starting point on Earth - results in the fact that the traveler sees the Earth moving away and approaching during times that are equal to one year, while the Earth, which is informed of the acceleration only by the arrival of light waves, sees the traveler moving away during two centuries and returning during two days, *i.e.* during a time forty thousand times shorter.

Now, if we look after the conditions under which a similar program could be realized, one encounters, of course, enormous physical difficulties.

The theory permits to calculate the work that the Earth should spend to launch the projectile, to transmit the kinetic energy corresponding to its enormous velocity. Assuming the mass of the projectile is only equal to one ton, it can easily be calculated if one wants to spend only one year to launch it, for example by turning it at the end of a sling before releasing it, then it should function nonstop for that year by four hundred billion horsepowers, and to produce them it must burn at least a thousand cubic kilometers of coal.

These difficulties at the beginning would be followed by difficulties not less large at the time of the reflexion or stop. We should first of all, for reflection, find a system capable of storing the enormous kinetic energy of the projectile, then restore it to return it in the opposite direction with the same velocity. To stop, one should gradually dissipate this energy without resulting at any moment in an acceleration or temperature elevation harmful to the projectile, while the amount of heat equal to its kinetic energy is sufficient to raise it to a temperature of 10^{16} degrees or more.

[53] We also have every reason to think that if a projectile coming toward Earth with such velocity, it wouldn't even notice its passage and would stop only at a certain depth in the soil without leaving any holes in the same area of the surface where this would have happened. It would hardly produce on its trajectory through the atmosphere a slight increase in electrical conductivity of the air. We know, indeed, by the example of α-particles of radium, *i.e.* the material atoms of helium with a velocity of just 20,000 kilometers per second, can follow a perfectly straight trajectory and cross through other atoms without leaving any trace of their passage other than increased conductivity, and our projectile has per unit mass a kinetic energy a hundred thousand times greater than α particles. It would be an

extraordinarily penetrating radiation. If we want to avoid these difficulties, we have to find a way to slow its motion gradually as it approaches Earth. It does not seem possible either to use the principle of the rocket that my friend PERRIN proposes for interplanetary travel.

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I developed these speculations, only to show by a striking example to which consequences, far away from the usual concepts, the new form of the concepts of space and time leads. It must be remembered that this development is based on perfectly correct determinations required by indisputable experimental facts, of which our ancestors were not aware when they constituted, in their experience in relation that synthesized mechanics, the categories of space and time which we have inherited from them. It's up to us to extend their work by pursuing with greater detail, in connection with the means at our disposal, the adaptation of thought to the facts.

It is not only in the field of space and time that the redesign of the most fundamental concepts of the mechanistic synthesis is required. The mass, which was measured by inertia, an essential attribute of matter, was regarded as an essentially invariable element, [54] characterizing a given portion of matter. This notion now vanishes and merges with that of energy: the mass of a piece of matter varies with the internal energy of it, rises and falls with it. A piece of matter which radiates, loses its inertia in an amount proportional to the energy radiated. It is the energy which is inert; matter can resist the change in velocity only in proportion of the energy it contains.

The concept of energy itself loses its absolute sense: its measurement varies with the reference system to which the phenomena are related, and physicists are currently, in the expression of the laws of the universe, looking after the real elements that possess an absolute sense, *i.e.* the elements that remain invariant when changing from one reference system to another, and which will play the role in the electromagnetic conception of the world, that which was played by time, mass and energy in the mechanistic synthesis.